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13. ABSTRACT (Maximum 200 words)

Multidimensional, reactive flow simulations were used to provide the pressure information on the projectile for studying the projectile stability and the starting process of the thermally choked ram accelerator. The results showed that the pressure distribution on the front part of the projectile was controlled by a series of reflected shock and expansion waves. These reflected pressure waves were quite stable and virtually steady. A perturbation in the projectile position could result in significant changes in the strength of these shock and expansion waves, but the overall structure of these pressure waves remained the same; On the rear part of projectile, there was a normal shock generated by the thermally choked combustion behind the projectile. This shock maintained the high pressure needed for the projectile acceleration. Unlike the reflected shock on the front part, this shock was transient. A perturbation in projectile position could change both the strength and location of this shock; When the center of projectile mass was in the middle of the projectile, the pressure imbalance created by the perturbation in the position stabilized the projectile if a normal shock was maintained on the rear of projectile by the thermally choked combustion. The pressure imbalance further destabilized the projectile if the normal shock was absent. The study on the starting process showed that the thermally choked combustion and the associated normal shock could be generated by either a pressure pulse, resembling that created by the obturator, or an ignition process on the rear part of projectile, resembling that generated by an on-projectile ignitor.

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NUMERICAL STUDIES FOR THE RAM ACCELERATOR

Final Report – August, 1995
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Status of Effort:

In the past year, we have focused on the projectile stability and the starting process of the thermally choked ram accelerator (Fig. 1). We used multidimensional, reactive flow simulations to provide the pressure information on the projectile for studying these issues. Our studies show that: (1) The pressure distribution on the front part of the projectile is controlled by a series of reflected shock and expansion waves. These reflected pressure waves are quite stable and virtually steady. A perturbation in the projectile position can result in significant changes in the strength of these shock and expansion waves, but the overall structure of these pressure waves remains the same; (2) On the rear part of projectile, there is a normal shock generated by the thermally choked combustion behind the projectile. This shock maintains the high pressure needed for the projectile acceleration. Unlike the reflected shock on the front part, this shock is transient. A perturbation in projectile position can change both the strength and location of this shock; (3) When the center of projectile mass is in the meddle of the projectile, the pressure imbalance created by the perturbation in the position stabilizes the projectile if a normal shock is maintained on the rear of projectile by the thermally choked combustion. The pressure imbalance further destabilizes the projectile if the normal shock is absent. (4) The study on the starting process shows that the thermally choked combustion and the associated normal shock could be generated by either a pressure pulse, resembling that created by the obturator, or an ignition process on the rear part of projectile, resembling that generated by an on-projectile ignitor.

Accomplishments/New Findings:

Pressure Distribution on the Projectile

We have performed numerical simulations of the reactive flow around the projectile at different positions in the thermally choked ram accelerator filled with the H_2:O_2:N_2/2:1:3.76 mixture. The inlet pressure and temperature of the mixture are 25 atm and 300 K, respectively. The projectile used in this study is the same as that used in the experiments at the University of Washington and the geometric specifications of the projectile are shown Fig. 2. The projectile velocity is 1250m/s and corresponding Mach number is 3.01. The studied projectile positions are: (1) the center line is located at the axis of the ram-accelerator tube, (2) the center line is translated 1.0 mm downward from the tube axis, and (3) the center line rotated 1.5° counterclockwise around the center of mass. For each projectile position, we performed three types of simulations: (a) A nonreactive flow simulation; (b) A reactive flow simulation with a simulated starting process which initiates the thermally choked combustion: The thermally choked combustion maintains a normal shock on the rear part of the projectile. (c) A reactive flow simulation without the simulated starting process: In this case, combustion occurs in a small region behind the projectile and is too weak to change the shock structure on the projectile. Therefore, there are no normal shocks on the rear part of the projectile and the pressure distribution on the projectile is very similar to that from the nonreactive simulation. In this case, the projectile does not accelerate.

Figures. 3-5 show pressure, Mach number, temperature, and water concentration around the projectile from the type-b simulations (with the starting process). The same figures also show the pressure profile on the projectile. When the projectile is centered, the shock structures and, therefore, the pressure distributions are symmetric on the upper and lower projectile surfaces. In the translated case, the strength of the reflected shock and expansion waves are quite different on the two surfaces while the locations of these waves remain similar. However, the strength and location of the thermally choked normal shock are largely the same on the both surfaces. In the rotated case, the locations of the reflected waves still remain similar on the two surfaces while the difference in the strength is pronounced. Both the location and strength of the normal shock differ significantly on the two surfaces.

Projectile Stability

Having obtained the pressure information on the projectile, we calculated the aerodynamic torque on the projectile with different centers of mass. The following two tables show the results from the type-b and type-c simulations. The projectile with its center of mass at 7.4 cm from the tip is very similar to that used in

the experiments and we will focus on this projectile. In this case, the torque on the centered projectile is quite minimal. The torque on the translated projectile is significant. Therefore, projectile translation leads to projectile rotation (canting). In the rotated case, the torque stabilizes the projectile if a normal shock is maintained on the rear part of the projectile by the thermally choked combustion. If the normal shock is absent, the torque augments the original rotation and, therefore, further destabilizes the projectile. Thus, the normal shock changes the stability characteristics of the projectile.

torque on the projectile per unit width from the type-b simulations (N-m/m) (with the normal shock generated by the thermally choked combustion)			
location of the center of mass from the projectile tip (cm) / projectile axis	3.4	7.4	11.4
centered	-4.0 to 3.0	-6.0 to 14.0	-40.0 to 30.0
translated	2.6 to 5.0×10^3	3.0 to 5.4×10^2	-2.3 to -1.4×10^2
rotated	-2.2 to -1.5×10^4	-9.0 to -5.5×10^3	2.8 to 3.2×10^3

torque on the projectile per unit width from the type-c simulations (N-m/m) (without the normal shock generated by the thermally choked combustion)			
location of the center of mass from the projectile tip (cm) / projectile axis	3.4	7.4	11.4
centered	-18.0 to 24.0	-2.0 to 10.0	-3.5 to 2.0
translated	1.8 to 2.4×10^3	3.2 to 4.5×10^2	-2.8 to -1.2×10^3
rotated	-5.2 to -3.5×10^3	2.3 to 8.5×10^2	1.0 to 1.6×10^3

Starting Process

The normal shock on the rear part of the projectile is not only crucial to the projectile acceleration but also important to the projectile stability. This shock is maintained by the thermally choked combustion behind the projectile. However, thermally choked combustion cannot be established without a proper starting process. In the experiments, the thermally choked combustion is initiated by a pressure pulse generated by an obturator initially located behind the projectile. Our time-accurate numerical simulation capability provides a tool to study this starting process. If a simulation is started without using any simulated starting processes, combustion is confined to a small region behind the projectile and the energy release from the combustion is far too weak to choke the flow and, therefore, to maintain a normal shock on the rear part of the projectile. The thermally choked combustion and the associated normal shock need to be generated by either a pressure pulse, resembling that created by the obturator, or an ignition process on the rear part of projectile, resembling that generated by an on-projectile igniter. This issue requires more detailed studies.

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Publications:

Detonation Structures behind Oblique Shocks, C. Li, K. Kailasanath, and E.S. Oran, *Physics of Fluids*, 6:1600, 1994.

Numerical Simulations of Transient Reactive Flows in Ram Accelerators, C. Li, K. Kailasanath, E.S. Oran, A.M. Landsberg, and J.P. Boris, to appear *Shock Waves*, 1995.

Detonation Structures Generated by Multiple Shocks on Ram-Accelerator Projectile, C. Li, K. Kailasanath, and E.S. Oran, Submitted to *Combustion and Flame*, 1995

Analysis of Pressure Distributions on Projectiles in Thermally Choked Ram Accelerators, C. Li, K. Kailasanath, and E.S. Oran, the 2nd Int. Workshop on Ram Accelerators, 1995.

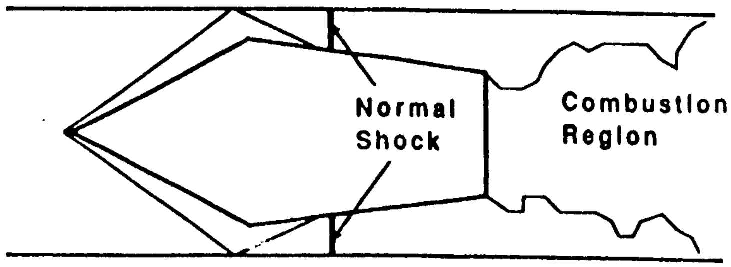

Fig. 1 Schematic of major reactive-flow features in a thermally choked ram accelerator.

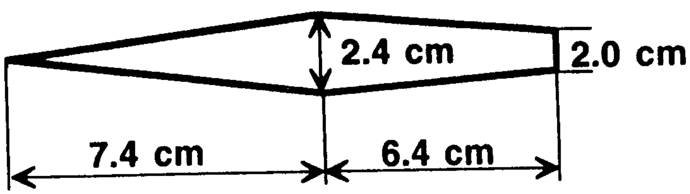

Fig. 2 Schematic of the projectile used in the simulations.

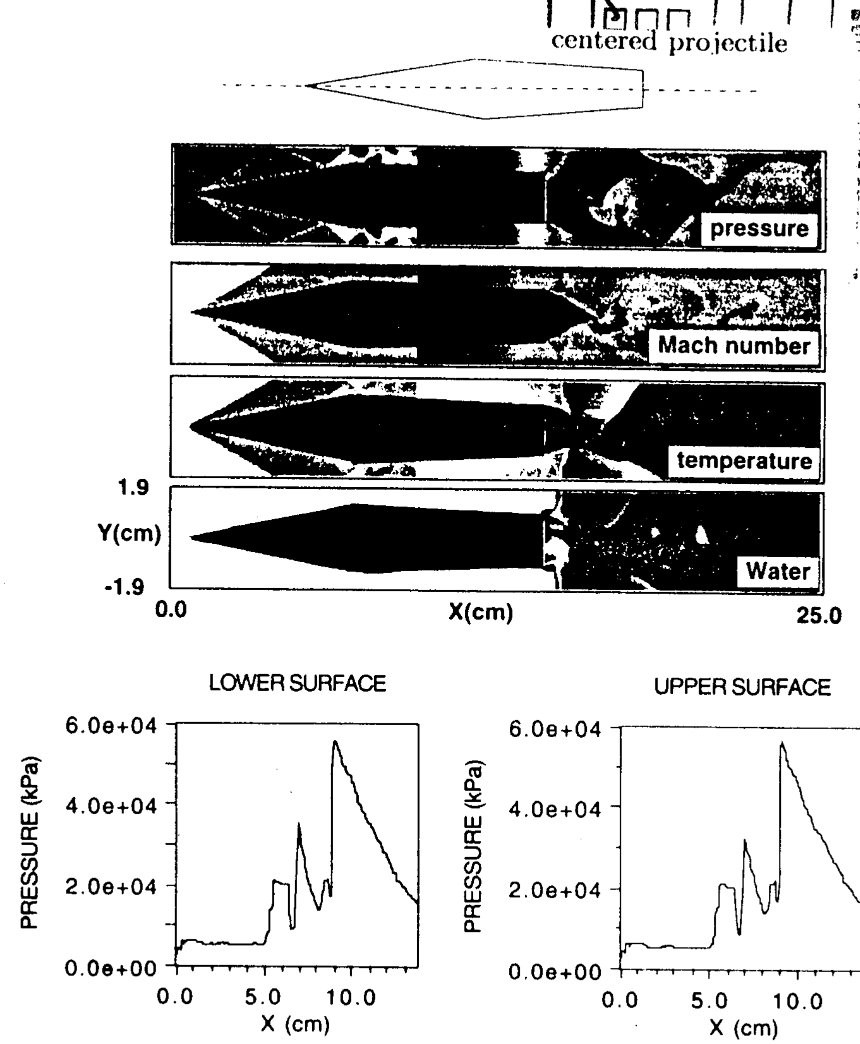

Fig. 3 Top figures: pressure, Mach number, temperature and water concentration from the simulation of the reactive flow around the projectile shown in Fig. 2 in the H_2:O_2:N_2/2:1:3.76 mixture. The projectile Mach number is 3.01 and, in this case, the projectile axis coincides with that of the launch tube. Bottom figures: pressure distributions on the lower and upper surfaces of the projectile from the simulation.

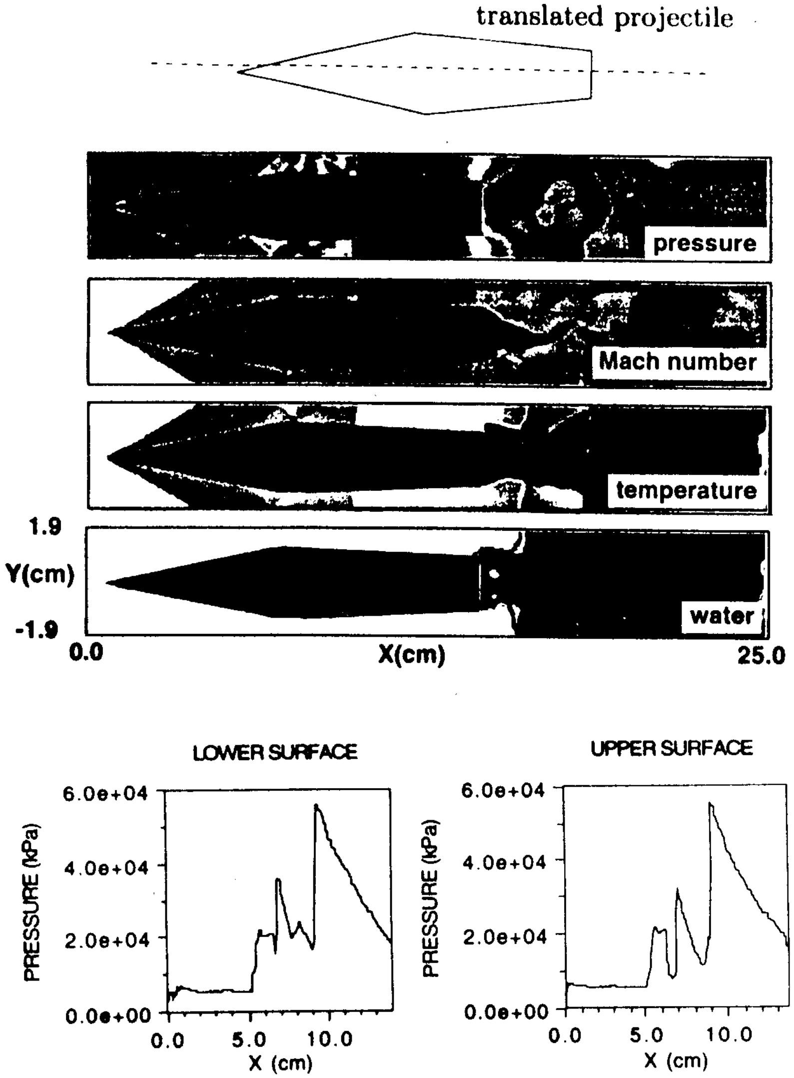

Fig. 4 Top figures: pressure, Mach number, temperature and water concentration from the simulation of the reactive flow around the projectile shown in Fig. 2 in the H_2:O_2:N_2/2:1:3.76 mixture. The projectile Mach number is 3.01 and, in this case, the projectile axis is translated 1.0mm downward from that of the launch tube. Bottom figures: pressure distributions on the lower and upper surfaces of the projectile from the simulation.

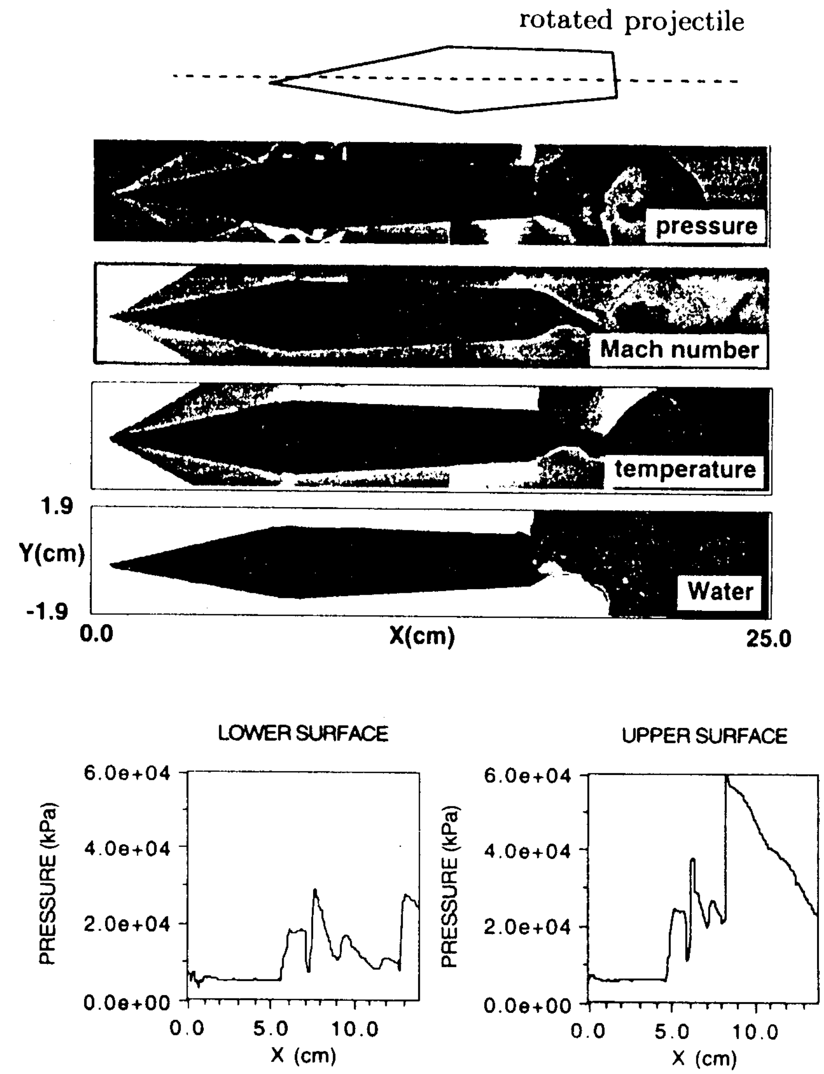

Fig. 5 Top figures: pressure, Mach number, temperature and water concentration from the simulation of the reactive flow around the projectile shown in Fig. 2 in the H_2:O_2:N_2/2:1:3.76 mixture. The projectile Mach number is 3.01 and, in this case, the projectile axis is rotated 1.5° counterclockwise form that of the launch tube. Bottom figures: pressure distributions on the lower and upper surfaces of the projectile from the simulation.